COMMERCIAL DEVELOPMENT OF ADVANCED PFBC TECHNOLOGY

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INTRODUCTION

In the 1970s, the coal-fired power generation industry recognized that the declining price of electricity over the previous five decades was coming to an end. Maximum use had been made of existing cycle efficiencies and scale-up. As researchers looked for a new approach, the focus shifted from the fully developed Rankine cycle to a new array of coal-fired plants using combined-cycle technology. Now, coal-fired combined-cycle plants are being introduced that shift power production to the Brayton cycle. Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) are two technologies at the forefront of this approach.

The PFBC approach burns coal in a fluidized bed combustor at elevated pressure. The plant generates electricity from a gas turbine (expanding the hot, pressurized products of combustion) in addition to the conventional steam (bottoming) cycle. Such a plant can achieve thermal efficiencies of about 40 percent and have a levelized busbar cost below any competing coal-based technology. In addition to the economic benefits, the "built-in" feature of environmental control (SO_2 and NO_x) in the combustion process eliminates the need for external gas cleanup such as scrubbers. A PFBC can burn a wider range of coals than a pulverized-coal-fired (PCF) boiler and is simpler to operate and maintain than an IGCC power plant.

By combining the salient features of PFBC and IGCC, a new generation of PFBC plants promises increased efficiency and lower cost, while avoiding the increased complexity and higher cost of the IGCC systems. Foster Wheeler's (Second-Generation) "Advanced" Pressurized Fluidized Bed Combustion concept achieves this goal. The partial conversion of coal to syngas and subsequent firing in a gas turbine at 1288°C (2350°F) increases the thermal efficiency of a PFBC plant to about 45 percent (HHV basis). Studies have further shown that 49 percent (HHV) efficiency can be achieved with high-pressure steam systems and advanced gas turbine technology under development.

The path to successful commercialization of APFBC technology involves conceptual design, pilot-scale component testing, integrated system testing, and demonstration. The developmental programs designed to achieve commercial status of the technology are described in the following sections.

ADVANCED PFBC CONCEPT

In Foster Wheeler's Second-Generation PFBC concept (Figure 1), coal is fed to a pressurized pyrolyzer (carbonizer), where it is converted to a low-Btu fuel gas and char. The relatively low carbon conversion that takes place in the carbonizer results in a simpler sulfur-removal process than is typically required in coal gasification processes. The char (unreacted coal, coal ash, and unreacted/reacted sorbent) that is produced in the carbonizer is transferred to a circulating pressurized fluidized bed combustor (CPFBC), where it is subsequently burned. The fuel gas produced in the carbonizer is cleaned of particulates and alkali and is fired in a specially designed combustor outside a high-temperature gas turbine using the CPFBC flue gas (vitiated air) as the oxidant. Steam is raised and superheated in the CPFBC.

The shaded components in Figure 1 represent the additional elements required to increase the efficiency of first-generation PFBC plants. The redistribution of electric power produced in first-generation PFBC plants (20 percent in the gas turbine/80 percent in the steam turbine) to that produced in second-generation PFBC plants (50 percent in the gas turbine/50 percent in the steam turbine) is shown in the figure.

COMPONENT TESTING—FWDC PILOT PLANT/UTSI

In Phase 1 of a three-phase, U.S. Department of Energy sponsored program, a nominal 500-MW plant was designed, and the costs, operational and environmental performance were compared with a conventional PCF plant with wet scrubbers. The plant is modular, with two parallel power island trains consisting of a carbonizer, CPFBC, and associated hot-gas cleanup systems feeding a gas turbine fired at 1288°C (2350°F) and a heat recovery steam generator

(HRSG). A single reheat steam turbine is powered by the combined steam flows of the two power island trains. About 45 percent of the combined-cycle power is produced by the two gas turbines and 55 percent by the steam turbine. Plant auxiliary power is very low (about 3 percent); the net thermal efficiency is 44.9 percent. The estimated heat rate of the plant is about 18 percent lower than the PCF plant. The results of the conceptual design study confirmed the objectives of the program—to design an APFBC plant with a 45-percent thermal efficiency and a cost-of-electricity (COE) 20 percent lower than a conventional PCF plant with flue gas desulfurization (FGD).

In Phase 2, a 254-mm (10-in.) carbonizer was tested at Foster Wheeler's Research Center in Livingston, New Jersey. Tests were conducted with operating temperatures ranging from 816 to 982°C (1500 to 1800°F) and pressures from 1.01 to 1.42 MPa (10 to 14 atm). Pittsburgh No. 8 coal and Ohio Plum Run dolomite were the predominant feedstocks, although Illinois No. 6 and Eagle Butte (a Wyoming subbituminous) were also tested, along with an Alabama limestone. Carbonizer fuel gas was predominantly carbon monoxide, carbon dioxide, hydrogen, and methane. No hydrocarbon vapors were produced throughout the entire test program—an important finding, since one of the major technology-related issues for this type of plant is the concern that hydrocarbon vapors, if present, could foul the barrier-type filters required to protect the high-temperature gas turbine from particulate erosion and deposition.

The pilot plant carbonizer test results, compared to the carbonizer performance assumptions used in the Phase 1 study, produced a higher fuel gas heating value, a higher sulfur-capture efficiency, and a lower yield of ammonia in the fuel gas. The better sulfur capture and lower ammonia yield (when converted to NO_x) result in lower plant emissions than predicted in the design study. The higher-quality fuel gas translates to a higher topping combustor firing temperature, a further increase in plant efficiency (44.9 to 46.2 percent), and an increase in power production in the gas turbine from 45 to 50 percent.

The carbonizer was subsequently converted to a 203-mm (8-in.) diameter x 11-m (34 ft-6 in.) tall CPFBC, and the CPFBC was tested using petroleum coke, four coals (Pittsburgh No. 8, Illinois No. 6, Kentucky, and Eagle Butte), char (produced in the earlier carbonizer tests), dolomite, and two limestone sorbents. Combustion efficiency was very high (greater than 99.5 percent) for all the fuels tested, including char. Sulfur capture efficiencies were generally high (greater than 96 percent) using Ca/S ratios ranging from 1:1 to 2:1. As a result of the "short" CPFBC height (the carbonizer was converted to the CPFBC), the NO_x and calcium sulfide conversions were not optimized.

Parallel to the pilot plant testing, Westinghouse has conducted topping combustor tests at the University of Tennessee Space Institute (UTSI). The topping combustor must burn low heating value fuel gas delivered from the carbonizer at approximately 870°C (1600°F) and 1.17 MPa (170 psi). The fuel gas entering the topping combustor has been previously cleaned of particulate and alkali, but contains fuel-bound nitrogen present as ammonia. The ammonia is significant because it will selectively oxidize to NO_x if the fuel is burned under the highly oxidizing conditions of standard turbine combustors. The fuel gas must be burned with the hot vitiated air from the CPFBC. The vitiated air has also been cleaned of particulates and alkali, but is partially depleted in oxygen. The 870°C (1600°F) vitiated air must be utilized to cool the topping combustor.

Tests completed with 305-, 356-, and 457-mm (12-, 14-, and 18-in.) diameter multiannular swirl burners (MASBs) using synthetically produced carbonizer fuel gas doped with ammonia confirmed that the MASB can be successfully cooled with 870°C (1600°F) vitiated air (supplemented with additional cooling air at the hottest locations). Good temperature distribution patterns were obtained and stable, complete combustion was achieved. To reduce ammonia conversion, the MASB was redesigned to improve backmixing and increase residence time in the rich zone.

In Phase 3, scheduled to begin in late 1994, a 254-mm (10-in.) I.D. carbonizer and 356-mm (14-in.) I.D. CPFBC—each with gas cleanup and solids feeding systems—will be tested in an integrated mode at the Foster Wheeler Research Center.

INTEGRATED TESTING—WILSONVILLE POWER SYSTEMS DEVELOPMENT FACILITY

In parallel with the pilot plant testing, work is under way to design and build a larger, integrated test facility. The test facility is part of the Power Systems Development Facility (PSDF) to be operated by Southern Company Services at Wilsonville, Alabama. The $145 million PSDF consists of several "modules" for long-term testing of APFBC, advanced gasification, hot-gas cleanup systems, and fuel cells. The PSDF is a joint, cost-shared effort between the DOE, the EPRI, and industry.

Most of the second-generation PFBC components will be tested in the Wilsonville configuration. The exception is a steam turbine is not incorporated in the design. The APFBC plant will provide the first full integration of the gas side of the power island—that is, operation of a gas turbine topping combustor with hot pressurized fuel gas from the carbonizer and hot pressurized flue gas from the CPFBC. A key element of the program is long-term testing and assessment of particulate control devices (PCDs) that directly supports DOE's Clean Coal program. The nominal 7-MW APFBC plant is scheduled to begin operation in late 1995.

The design coal and sorbent are Illinois No. 6 and Longview limestone. Eagle Butte subbituminous coal is an alternative fuel. The plant is designed for a coal feed rate of 0.69 kg/s (5500 lb/h) and a sorbent feed rate of 0.13 kg/s (1050 lb/h). Provision has been made in the design to test the CPFBC under low excess-air conditions, feeding coal and sorbent directly to the CPFBC.

The carbonizer, like the Livingston pilot plant unit, is a "jetting" fluidized bed pyrolyzer without heat-transfer surface. The refractory-lined vessel has a bed section (lower part) [approximately 914 mm (3 ft) diameter], 14.6 m (48 ft) high and a disengagement section (upper part) [approximately 1.22 m (4 ft) diameter]. The carbonizer is designed to feed coal pneumatically in the bottom of the vessel; alternate feed points are located radially at two different elevations. The feed system has been designed to accommodate both dry and paste feed.

The CPFBC, shown in Figure 2, is a refractory-lined vessel with an 838-mm (33-in.) diameter upper section. The integrated heat exchanger is a refractory-lined vessel that contains four cells—an inlet, an outlet, and two heat transfer cells. Heat is removed in the integrated heat exchanger by a once-through condensate system. The unit has been designed so that it can operate between 20- and 300-percent excess air to test both first-generation and advanced PFBC concepts. An oxidizer/cooler cools the CPFBC bed material from 871 to about 260°C (1600 to about 500°F) and transports the bed (ash) to a lockhopper for discharge from the unit.

High-temperature gas cleaning (HTGC) systems control particulates and alkalies. Two independent HTGC systems handle the carbonizer fuel gas stream and the CPFBC flue gas stream. Each HTGC system consists of a cyclone, PCD, and alkali getter.

An Industrial Filter & Pump Mfg. Co. low-density fiber ceramic candle filter design is being used as the carbonizer PCD. The refractory-lined filter vessel (Figure 3) has a 1.5-m (60-in.) diameter and contains candles arranged in six groups for back-pulse cleaning. The candles are of aluminosilicate fiber construction, with binders of silica and alumina. The monolithic flared flange and end cap of the candle are of densified ceramic fiber construction, as are the tubesheet and the candle retainer.

PCD service for the CPFBC will be provided by a Westinghouse ceramic candle filter consisting of a refractory-lined pressure vessel containing six arrays, or "clusters," of 60-mm (2.36-in.) diameter x 1.5-m long (59-in.) diameter candle elements. The individual clusters are supported from a high-alloy tubesheet and expansion assembly that spans the 3.1-m (10.2-ft) pressure vessel and separates the "clean" and "dirty" gas. The Westinghouse cluster concept is illustrated in Figure 4.

The alkali getters are sorbent packed beds contained in vertical, refractory-lined pressure vessels. The sorbent material reacts irreversibly with sodium and potassium vapor-phase compounds at high temperature.

The topping combustor is designed to operate with a vitiated air temperature of 1600°F, however, there is provision to introduce compressor air upstream of the topping combustor to cool the vitiated air to about 1400°F before it enters the topping combustor. The topping combustor is fired at an exhaust gas temperature of 1288°C (2350°F), the firing temperature for a commercial plant, using 899°C (1650°F) carbonizer fuel gas. While the advanced PFBC commercial plant uses an advanced industrial turbine with a turbine inlet temperature of 1288°C (2350°F), Wilsonville uses a turbine which operates at a maximum temperature of 1080°C (1975°F). Wilsonville will demonstrate that a firing temperature of 1288°C (2350°F) is viable with respect to emissions and burner design. However, because of the lower turbine operating temperature required, part of the compressor air will be used to cool the exhaust gas downstream of the topping combustor.

The gas turbine generator set is a modified Allison Model 501-KB5 gas turbine, which drives a synchronous generator through a speed-reducing gearbox. The hot exhaust gas from the topping combustor is expanded through the gas turbine, powering both the electric generator and the air compressor. Air from the compressor supplies all APFBC plant process air requirements.

DEMONSTRATION

A 95-MW plant utilizing Foster Wheeler's Advanced PFBC technology will be demonstrated under the U.S. Department of Energy's Clean Coal Technology V (CCT V) program. The proposed plant will operate in a cogeneration mode, providing electric power and extraction steam for manufacturing. Following a 30-month demonstration period, the plant will continue to operate on a commercial basis. The plant is scheduled to start up in 1998.

Coal paste and limestone are fed to the carbonizer, and the char from the carbonizer, additional coal paste, and limestone are burned in the CPFBC. The carbonizer is a refractory-lined vessel approximately 14 m (46 ft) high. The lower (bed) section of the carbonizer is 2.6-m (8-ft) diameter while the upper section of the vessel expands to 3.3-m (10-ft) diameter. The gas in-bed residence time is about 5 seconds, equivalent to the pilot plant and Wilsonville designs. The CPFBC is a Foster Wheeler single-vessel design incorporating membrane wall construction, cyclone, "J" valve, integrated heat exchanger (INTREX™), and ash stripper/cooler—all housed in a pressure vessel.

The CPFBC generates steam from the waterwalls and INTREX™, and additional steam is generated in the HRSG to drive the steam turbine generator. At full load, Four Rivers will generate about 70 MW of electricity and provide 39.1 kg/s (310,000 lb/h) steam at 1.31 MPa absolute (190 psia) and 215°C (420°F). The gas turbine generates 38 MW, and the extraction/condensing steam turbine generates 32 MW.

The particulate matter in the carbonizer fuel gas is removed using multiple ceramic candle filter systems supplied by Westinghouse. The CPFBC flue gas particulate matter is removed using a proprietary ceramic candle filter design supplied by Lurgi-Lentjes-Babcock (LLB), formerly Deutsche Babcock Energie. Seven 457-mm (18-in.) MASBs fire the carbonizer fuel gas in the topping combustor. The hot exhaust gas from the topping combustor drives a Westinghouse Model 251 gas turbine.

BEYOND DEMONSTRATION

Following demonstration, the APFBC technology will be ready for rapid world-wide commercialization. When proved successful, the technology will allow the effective use of high-sulfur coal, lower power generation costs, reduce emissions, extend fuel supplies, and provide utilities and industry with a reliable option for repowering and new generation capacity. As coal continues to play an important role in power generation, Advanced Pressurized Fluidized Bed Combustion will provide one of the most cost-effective and environmentally friendly technologies in the next century. Foster Wheeler is committed to the successful commercialization of this technology.

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